

DEPLOYMENT/RETRACTION GROUND TESTING  
OF A LARGE FLEXIBLE SOLAR ARRAY

Darius T. Chung  
Lockheed Missiles and Space Co.

ABSTRACT

In 1974, NASA Marshall Space Flight Center awarded to Lockheed Missiles and Space Co. a contract for a large (4 meter x 32 meter) flexible fold-up solar array. Under this contract a technology program was started at LMSC resulting in conceptual studies, design, fabrication, and ground test of a prototype solar array with the goal of eventual flight of this array as an experiment aboard the Space Shuttle. This paper addresses the simulated zero-gravity ground testing of the solar array consisting of eighty-four full-size panels (.368 meter x .4 meter each) and involving automatic, hands-off extension, retraction, and lockup operations.

Three methods of ground testing were investigated:

1. Vertical testing, similar to that previously conducted in a space station solar array program at LMSC
2. Horizontal testing, using an overhead water trough to support the panels
3. Horizontal testing, using an overhead track in conjunction with a counter-weight system to support the panels

Method 3 was selected as baseline.

The test structure is made up of three sections; namely, the wing-assembly vertical support structure, the five-tier overhead track, and the mast-element support track.

The flexible solar array wing assembly was successfully extended and retracted numerous times under simulated zero-gravity conditions. These tests have significantly contributed to the flexible solar array design development and ultimately to the potential success of the solar array shuttle flight experiment.

## INTRODUCTION

Lockheed Missiles and Space Co. (LMSC), in conjunction with the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Alabama has had the responsibility for the design, development, manufacturing, and ground testing of a large-area flexible solar array. The flexible solar array blanket assembly consisting of eighty-three mass-simulated panels and one electrical panel is required to partially extend, fully extend, partially retract, fully retract, and lock up to its fully preloaded stowage mode.\* These operations must be performed automatically and demonstrate hands-off, proper unfolding, folding, and lock-up. The simulated zero-gravity, ground test structure developed under this program provided the capability to perform these tasks.

## BASELINE SELECTION

During the proposal stage three methods of simulated zero-gravity testing were investigated.

**VERTICAL TESTING.** This test method was considered first because of LMSC's prior vertical testing experience in connection with a space station solar array contract (NASA Contract NAS9-11039). The total deployed blanket assembly area of this design was approximately 10,000 sq ft, and for ground test one quadrant (2500 sq ft) was automatically

\*NASA Contract NAS8-31352

deployed sequentially. The quadrant was made up of five individual sub-blanket assemblies, each with a deployed area of 504 sq ft (6 ft x 84 ft), in order to achieve sequential deployment. For ground testing the solar panel container assembly and the mast canister were mounted at floor level. The array was then deployed upward. Automatic counterbalancing of the deploying array was used to counteract the gravity forces. The cover, outboard supports, and each mast element were individually counterweighted, however the solar panels were counterweighted only through the outboard supports at the upper end of the deploying array from which the solar blanket was suspended. In this design, retraction was not a requirement. Consequently, gravity and test personnel were employed to assist in the refolding of the sub-blanket assemblies during a retraction. As a result of sequential deployment and because no retraction was required, vertical testing was the most economically feasible method to use.

This test method does not require counterbalancing individual panels. However, the top-most hinge must have the capability to support the total weight of the panels, and the load capability of each adjacent lower hinge can be decreased by the weight of a panel. The alternatives to varying hinge capabilities can be to counterbalance each panel (a very difficult task), or design all the hinges to the maximum capability (a highly over-designed hinge for flight). Counterbalancing, however, must be provided for all other deployed structure such as a cover, outboard supports, and the deployable mast elements.

**HORIZONTAL TESTING.** This method utilizes an overhead water trough which supports the deploying/retracting blanket assembly through a series of floats. Individual panels and their respective counterweights are vertically supported by the floats and would deploy horizontally. A series of questions resulted from this concept that raised doubts about success, such as:

1. Water leakage and spillage would fall on the assembly and the floor
2. Water on the floor could create a safety hazard
3. Float thickness would negate minimum stack height, which would affect lock-up capabilities
4. Damp atmosphere may create corrosion
5. Stagnant water would have to be replaced periodically.

HORIZONTAL TESTING--BASELINE. This method uses a counterweight system to counterbalance the vertically hung blanket assembly, which deploys and retracts horizontally. As compared to the vertical test method, a single flight-qualified hinge design is all that is necessary, because it is not affected by gravity. However, a ground test support loop at one end of each panel is required to attach the panel to its counterweights. As in vertical testing, the cover assembly and the outboard mechanism assemblies require counterbalancing--but not the deployable mast elements. An inexpensive eight-panel full-scale test model was built and manually operated. The demonstration was very successful and justified the selection of the test method (see Figure 1).

#### THE BASELINE SIMULATED-ZERO-GRAVITY TEST STRUCTURE

FULL-SCALE WING ASSEMBLY TEST OBJECTIVES. The selection of the test method was made on the basis that it could fulfill all of the test objectives. They are as follows:

- Demonstrate large area solar array hardware handling technology
- Demonstrate development, qualification, and acceptance test techniques
- Demonstrate simulated-zero-gravity, automatic hands-off wing assembly operation
  - Unlocking and locking of the cover assembly
  - Operation of the blanket assembly tensioning system
  - Full and partial deployment/retraction of the mast
  - Simulation of the zero-gravity fold-up
  - Attain planar configuration of deployed or partially deployed blanket assembly

The simulated zero-gravity ground test structure was designed and manufactured by LMSC, and is made up of three sections. The first section is the wing assembly vertical support structure which is supported at each end by bearings, allowing rotation of the wing assembly during extension and retraction. Concentricity of these end bearings was very critical during ground test. The rotation capability was also necessary to install the wing assembly to the test hardware. The second section is the overhead

test structure which is made up of a five-tier track section approximately 33.5 meters long. The tracks are the surface for the roller assemblies which support the counterweights and their respective panels, the cover, the locking level mechanism, the mast tip fitting, and the deployed-panel tension distribution bars during extension and retraction operations. The third section is a mast element support track structure approximately 37 meters long which is sloped on one end. This track is the surface for ten wooden dollies that are attached to each other by nine nylon tie strings approximately 3 meters long. Another tie string, 1.5 meters long, attaches the lead dolly to the mast tip fitting of the wing assembly. These dollies and their tie strings are so designed as to provide intermittent support for the mast elements of the Able-Engineering Deployable Mast Assembly during extension and retraction of the wing assembly. During retraction the sloping surface of the track allows the dollies to move away from the retracting mast as it is stowed in its stowage canister (See Figure 2 and Figure 10).

**WING ASSEMBLY VERTICAL SUPPORT STRUCTURE.** This section of the ground test structure supports the solar array wing assembly through its container assembly. The container is mounted on this support structure at four attach points, which are the same points to be used to mount the solar array wing assembly in the Shuttle for flight. A master hole location tool plate is used to assure precise location of the holes. As shown in Figure 3, the support structure is made up of three sections; namely, the container center crank support assembly, the upper end support assembly, and the lower end support assembly. The center crank structure is an all-aluminum welded assembly made up of a five-inch pipe and its right-angled ends. The two container attach plates are located approximately 40 percent and 80 percent below the top of the pipe. Consequently, the upper container attach point is further away from the top end than its counterpart is from the lower end. To assure a stable top end, the longer upper support was required. The upper end support is a bolted assembly and in turn is attached to structure that is part of the test facility. It houses the upper end support thrust bearing. The lower end support is a stand-off assembly that is merely attached to the floor, and it houses the lower end support bearing. The upper and lower bearings must be vertically aligned to achieve a balanced condition and thus eliminate a built-in tendency of the center crank structure to rotate. Up-and-down adjustment is also necessary to

center the container assembly to the vertically supported blanket assembly. In addition, the container attach plates have provisions for attaching a ground handling fixture so that the fully preloaded wing assembly can be installed on the ground test structure.

**THE OVERHEAD TEST STRUCTURE.** As shown in Figure 2, the overhead test structure is a 33.5-meter-long five-tier track assembly. The five-tier tracks are a bolted assembly, five of which are 6 meters long and one that is 3.5 meters long. Figure 4 is a typical bolted area of the five-tier track. In addition, on top of each track is a 33.5-meter-long continuous steel strip (.042 inch thick). On top and along the outer edge of the strip is a series of square roller guide bars that are butted to each other (they are not shown for clarity). Figure 5 shows the strip, roller guide bars, and roller assembly on a track. It also shows that, the roller assembly is tee-shaped with each pair of vertical rollers supporting the panel and its counterweight, and the pair of horizontal rollers providing guidance. Each roller assembly supports two panels and their respective counterweights, which are at different levels (see Figure 2). This is necessary to allow the counterweights to swing freely as the panels of the blanket assembly travel from their stowed to deployed positions. The first and last roller assemblies, however, support only their own panel and counterweight.

Figure 6a shows the roller assemblies in the stowed position on their respective tier level. Tiering is necessary to assure the thinnest stack of folded panels in the blanket assembly. Figure 6b shows a roller assembly supporting two counterweights and its respective panels in an operating mode. Note the mini-counterweights which are looped around the thin section. They can be moved in either direction to a final position so as to obtain a near-perfectly balanced situation of all the panels in the blanket assembly. Near-perfect balance is when the hinge lines of the folded blanket assembly are in line. This task is very tedious because movement of the mini-counterweight of one panel affects the balanced position of its adjacent panels. It should also be performed in a retracted, but not stowed, position. As a suggestion, one may consider removing the hinge pins, obtaining the near-perfect balance, fixing the position of the mini-counterweight and re-installing the hinge pin. Figure 6c and Figure 7 show the panel edge ground test support loop and the edge support rod that attaches to the counterweight by its support cables. Figure 6d illustrates the three positions of the blanket assembly.

Two other similar roller assemblies are also used to centrally support the intermediate and inner panel tension distribution bars. These bars through a negator spring motor system tension and establish planarity of the partially and fully deployed blanket assembly. The cover assembly and its two-axis counterweight system, the mast tip fitting (see Figure 8), and the whiffletree locking lever assemblies (see Figure 9) are supported by three similar and larger roller assemblies. The two-axis is necessary for the cover assembly because it requires counterbalancing sideways so its edges are parallel with the panel hinge lines and fore and aft to obtain parallelism to the base of the container assembly. The mast tip fitting does not require counterbalancing because it is centrally supported by the overhead structure. Figure 9 shows the whiffletree locking lever assembly is counterbalanced by a rotating weight. Tie cables with adjustable turn-buckles attach to the upper pair of locking levers only. The lower pair is then supported through the locking lever linkage mechanism and the geometry allows simultaneous movement of the levers.

**MAST ELEMENT SUPPORT TRACK.** This is the third section of the ground test structure and is totally made of wood with one exception, the adjustable steel cable diagonals. The track length is approximately 37 meters long and is made from ten 3.08-meter-long sections and one 6.76-meter-long sloping section. The end of each section is supported to a predetermined height by an offset tee/cross-over diagonal assembly. Every other pair of these assemblies is tied together by the diagonal steel cables and adjusted to its proper tension to assure stability. Under each assembly is a pair of height adjustment screws and two lock nuts per screw to obtain a flat level track. The dolly roller surface is made of particle board, and the butted end of each section of track is filled with wood putty, then sanded to a smooth surface thus eliminating surface irregularities (see Figure 2 and Figure 10). A series of dollies with wheels that are free to rotate support the mast elements as it is deployed. The lead dolly is tied to the mast tip with a nylon tie string. All subsequent dollies then tie to each other, and the maximum length of the tie strings is determined by the maximum length of unsupported mast. This information must be obtained from the mast subcontractor. When the mast is fully stowed, the dollies are butted against each other on the sloping surface of the track. As the mast deploys, the lead tie string, shortly thereafter, becomes taut and pulls the lead dolly up the slope. The dolly is positioned under

the mast, thus providing the necessary support for the mast. This operation repeats itself for all subsequent dollies during partial or full deployment operations. During retraction the operation is reversed (see Figure 10).

**CONCLUDING REMARKS.** The vertical support structure and the mast element structure track were straight-forward designs and did not require any special tooling. Not so for the five-tier overhead support track. The materials used to build the five-tier assembly sections were standard aluminum extrusions and engineering accepted them as received. It was imperative that the roller assembly surface be flat, so a tool was designed and manufactured to achieve this. In order to obtain the required flatness, tapered shims were used between the vertical tees and angles (see Figure 4). Another very important reason for the tool is to assure an exact match at the butted end of each five-tier section to its adjacent section.

The first roller assembly did not have the horizontal guide rollers nor did the overhead structure contain the roller guide bars. This was unreliable when demonstrated on the actual structure. Any dirt or surface irregularity resulted in a binding situation and in some cases the roller assembly rotated ninety degrees and fell through the cable clearance gap. The present design was an outstanding solution. In addition, friction in the system is negligible. Another part which contributed to the successful elimination of the roller assembly binding was the continuous steel strip. Initially a .007-inch-thick continuous steel strip was used. When rolled out it was impossible to acquire a flat surface and a single straight edge. The edge was a long curve. Consequently, every instance of straightening the curve resulted in an irregular (puckered) rolling surface.

Simulated zero-gravity testing of the flat-fold flexible solar array wing assembly demonstrated the adequacy and feasibility of the ground test structure. All the objectives were achieved, thus justifying the selected design. The knowledge gained has provided invaluable assistance and has significantly contributed to the design and development of other flexible and rigid solar array systems.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge and express his appreciation to the following individuals for their contributions to the success of the Ground Test Program .

Mr . Rick Elms, Program Project Leader, who provided valuable background information for this paper in the form of documented activity reports and various design review presentations .

Mr . Dave Omori, Senior Design Engineer, who was given the responsibility of developing the idea of the test structure and through his ingenuity minimized most of the manufacturing and test problems on his original layout .

Mr . John Cayori, Skunk Works Leadman, had an excellent knowledge of the total design, and as a result resolved most of the manufacturing and test problems . He continuously displayed a natural instinct to create, develop, and build numerous shop aids to minimize and/or eliminate various problems, thus saving the program valuable time and money.



Fig. 1 Eight-panel Full-Scale Demonstration Model

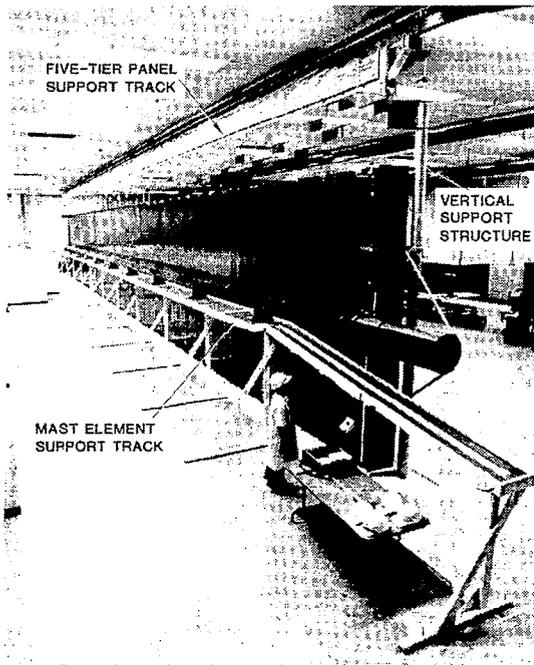


Fig. 2 Fully Deployed Wing Assembly

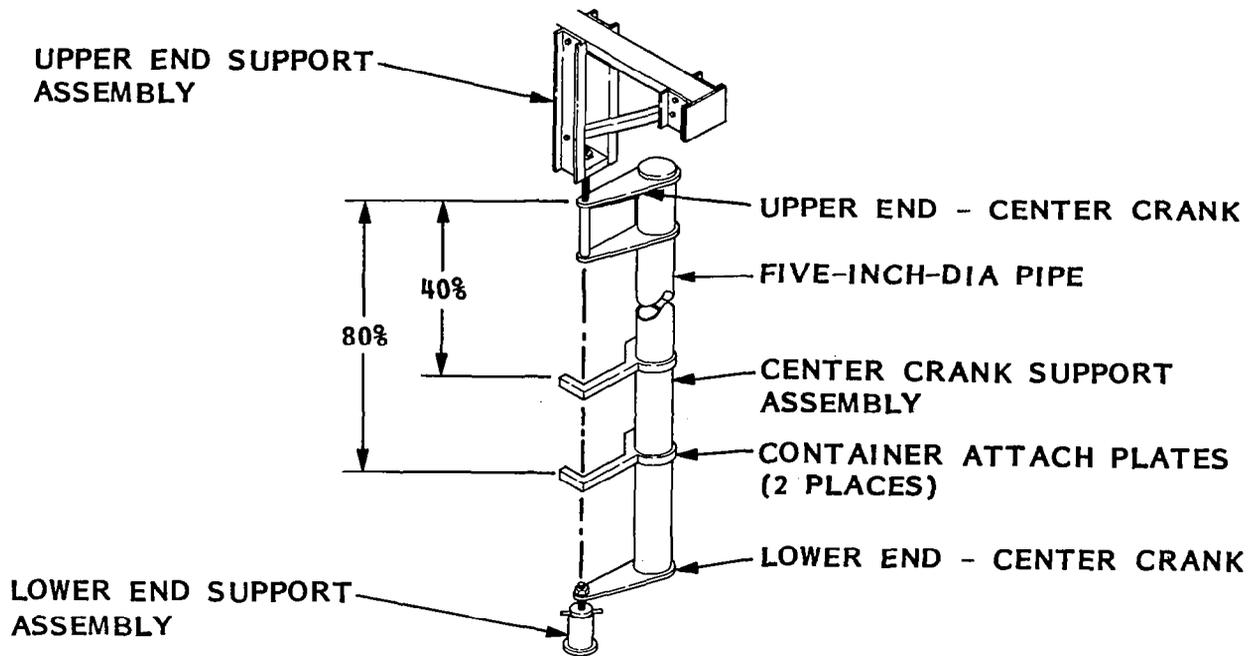


Fig. 3 Vertical Support Structure

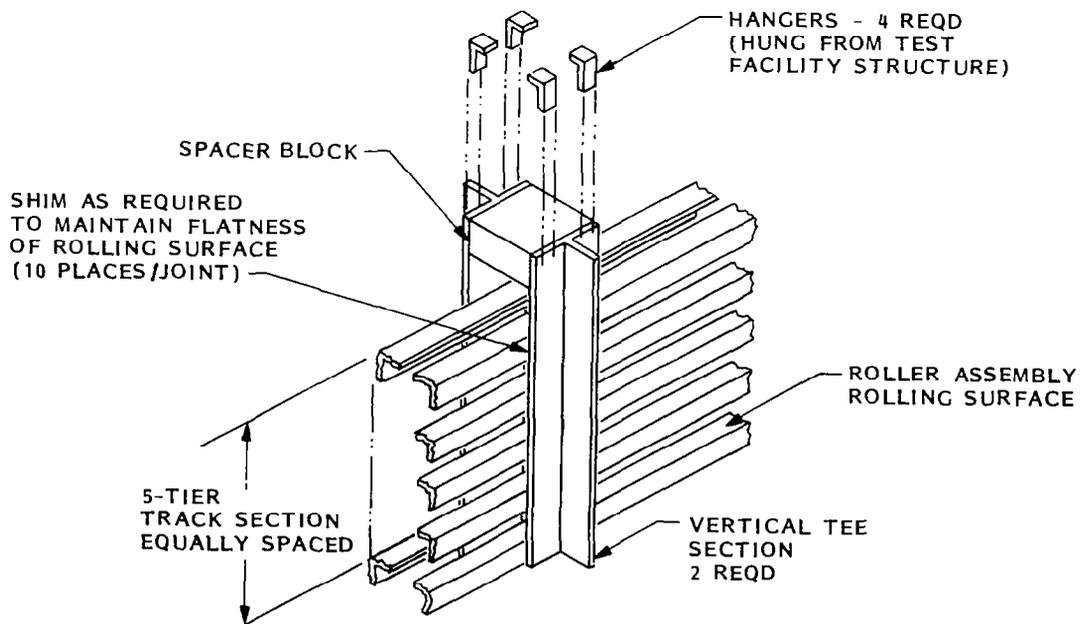


Fig. 4 Typical Bolted Area at the Joints and In between Joints (Strip and Square Bars Not Shown for Clarity)

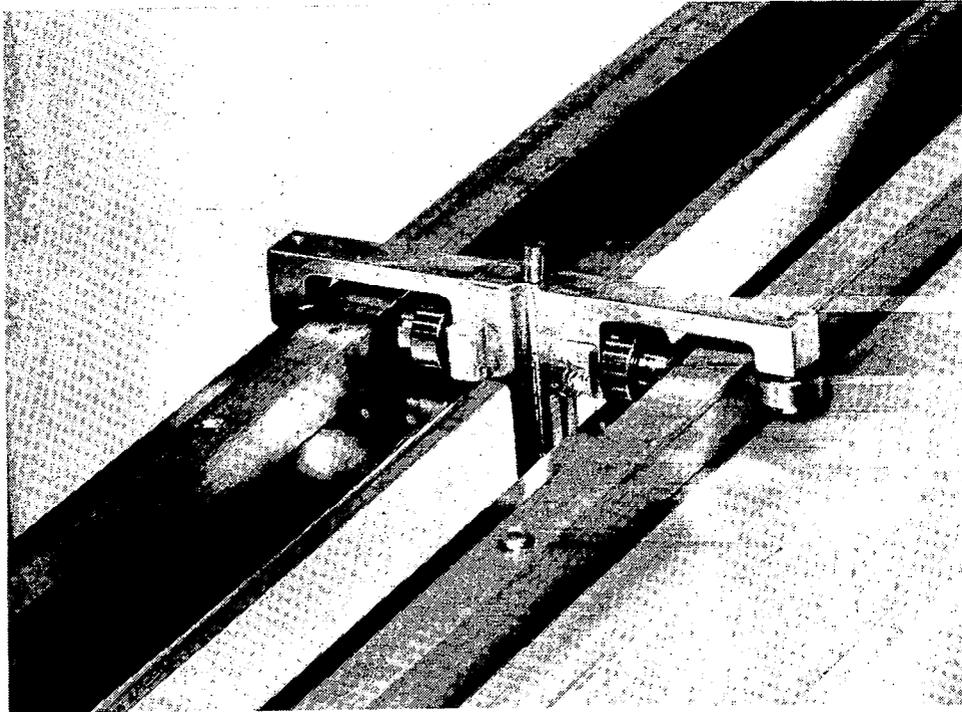


Fig. 5 Panel Roller Support Bearing

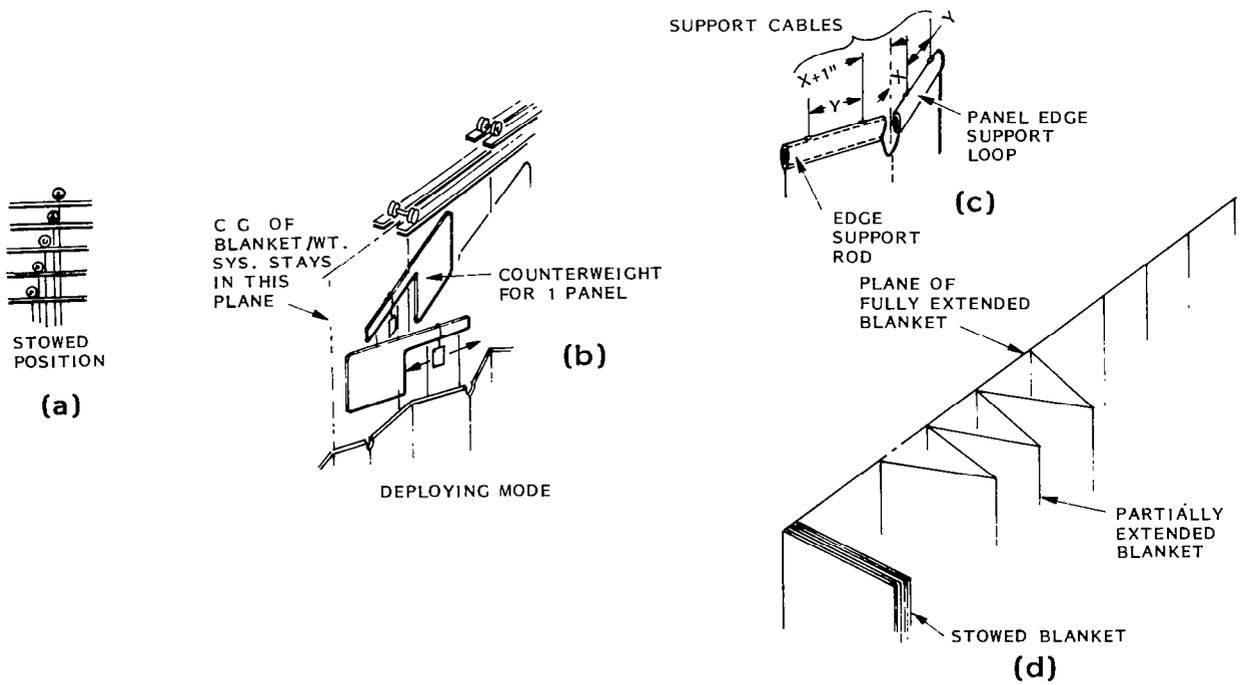


Fig. 6 Extension of Flat-fold Array

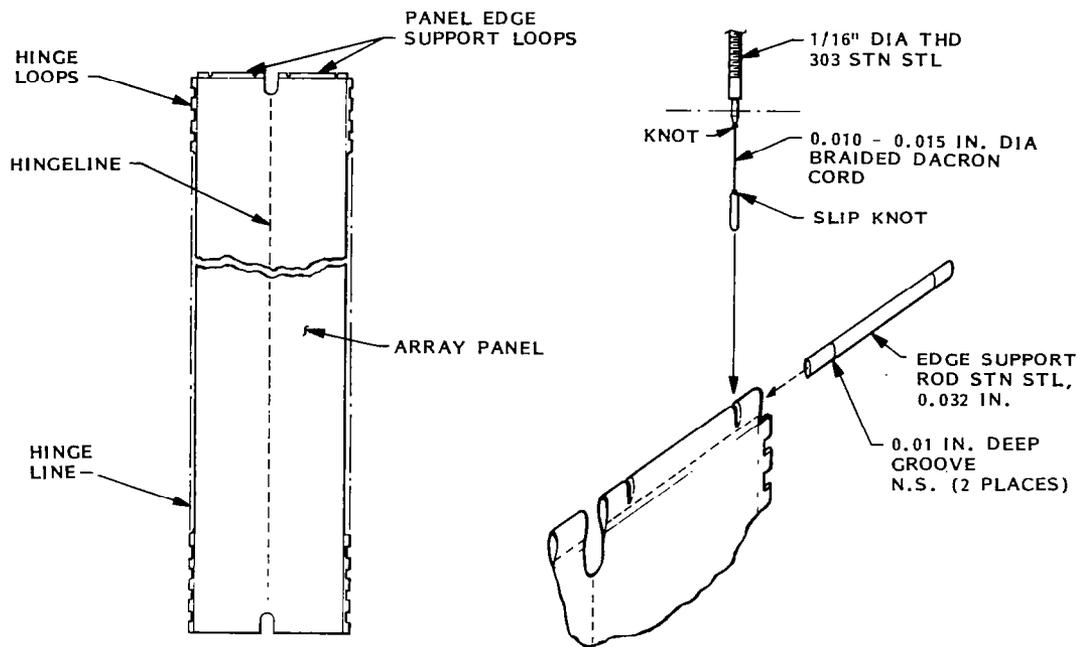


Fig. 7 Array Panel Edge Support Design

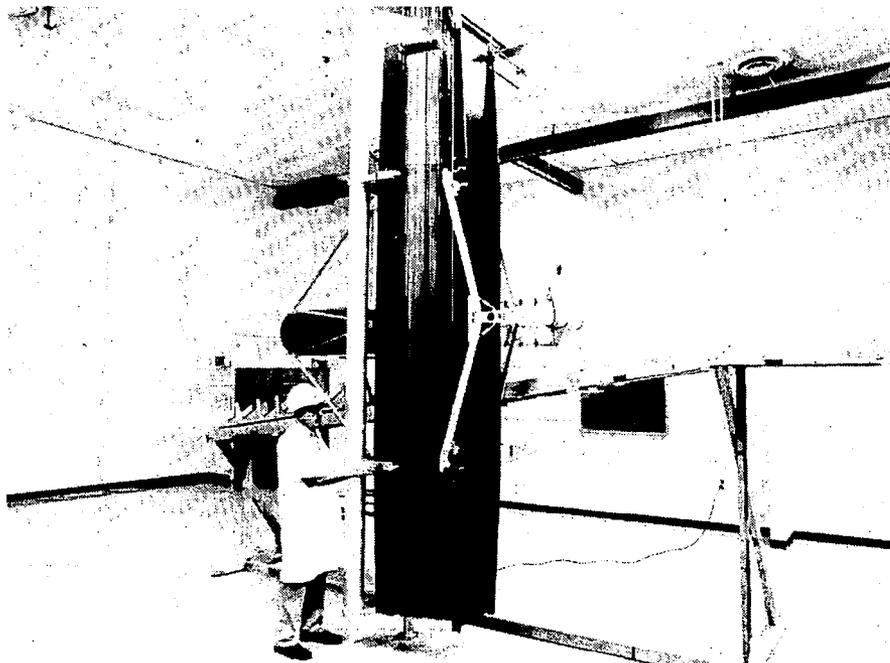


Fig. 8 Cover Assembly Two-axis Counterbalancing System and the Mast Tip Fitting

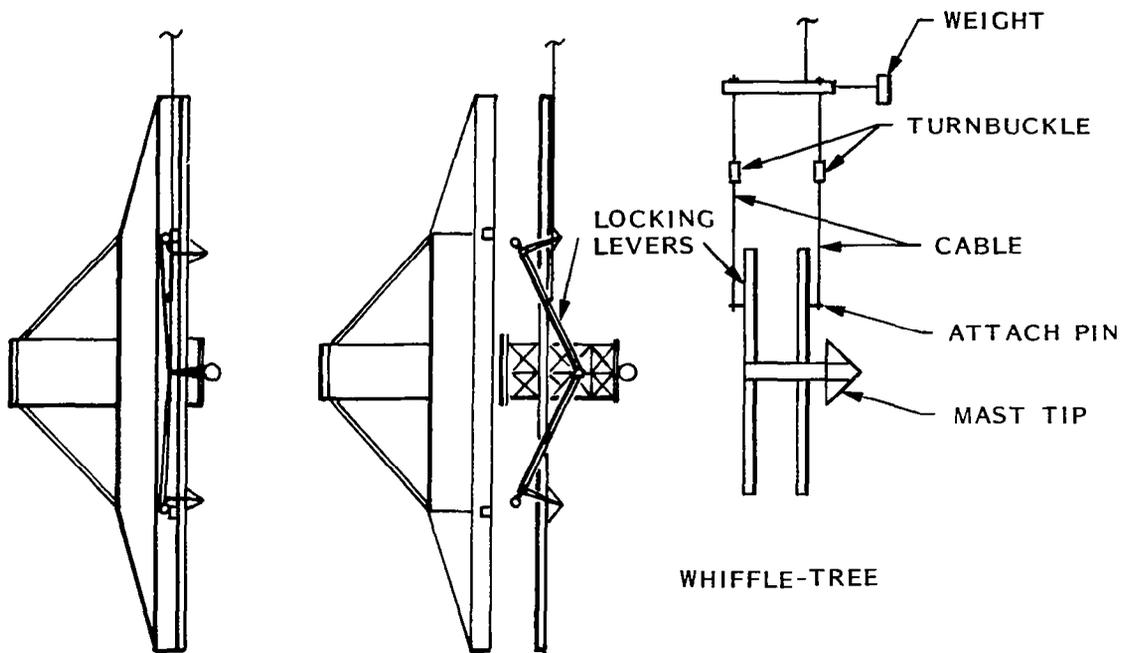


Fig. 9 Box Cover Locking Mechanism

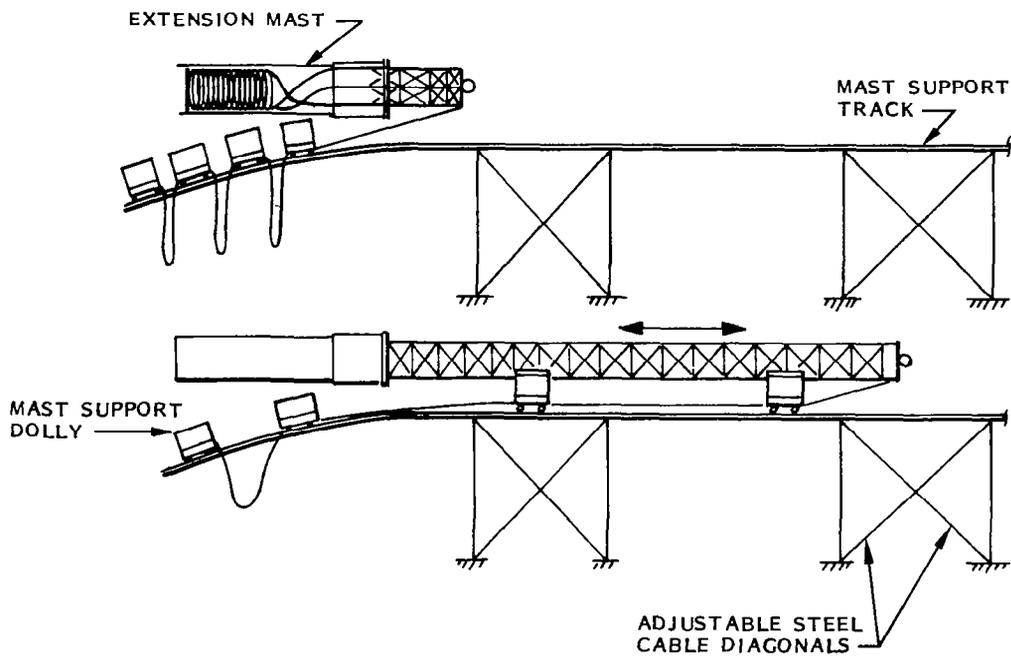


Fig. 10 Coilable Longeron Extension Mast (CLEM)

Darius T. Chung  
Lockheed Missiles and Space Company  
P.O. Box 504  
Sunnyvale, California 94088

Mr. Chung is presently the responsible engineer for the hold-down and release and the deployment motor/gearhead mechanisms of the P-375 solar array system. He is also responsible for the Solar Electric Propulsion Solar Array Flight Experiment (SEPSAFE) that will be included in the cargo on one of the Space Shuttle flights. He has been involved in mechanical design with Lockheed since 1961. Specific areas of involvement have been deployable systems such as rigid and large area flexible solar arrays, large area parabolic antennas, and deployable/retractable systems of other large area flexible solar arrays. Since 1976, he has flown on numerous zero-g flights in a specially designed KC-135 aircraft as Lockheed's test coordinator relating to SEP flexible solar arrays.